A REGIONAL CLIMATE-HYDROLOGY MODELING SYSTEM FOR CLIMATE AND WATER RESOURCES APPLICATIONS

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Introduction

Water is a vital resource for human as well as the natural ecosystems. The availability of water is greatly influence by climate conditions that vary on seasonal, interannual, and decadal time scales. Climate variations and change can affect both frequency and severity of floods and drought. A regional climate-hydrology modeling system has been developed at the Pacific Northwest National Laboratory (PNNL) for climate and water resources applications. The modeling system has been applied to determine the potential impacts of climate change on water resources. It has also been applied to demonstrate the usefulness of seasonal climate forecasts for water resources management. This paper briefly introduces the regional modeling system and some recent applications.

The regional modeling system consists of a regional climate model (RCM) and a fully distributed hydrology model. The RCM is based on the National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) (Grell et al. 1993). Because land surface heterogeneity is a prominent characteristics over many regions of the world, correct representations of surface topography and land cover and their impacts on precipitation and land surface hydrology is critical for coupling climate and hydrology models. One notable feature of the PNNL RCM is the subgrid parameterization of orographic precipitation (Leung and Ghan, 1995; 1998). The model aggregates subgrid variations in surface topography into a limited number of surface elevation classes. An airflow model and a thermodynamic model are used to account for the effects of subgrid topography on cloud and precipitation processes. The subgrid parameterization is schematically illustrated in Figure 1 with an example of the Middle Fork Flathead watershed in Montana. Cloud, radiation, turbulence transfer, and surface processes are all calculated per each elevation class of each model grid cell. This way, the RCM can operate at a coarser spatial resolution (typically 60-100 km) while still accounting for subgrid spatial heterogeneity in surface topography which impacts local hydrology, but at a reduced computational cost. Simulations performed with the RCM applied over the Pacific Northwest (e.g., Leung and Ghan, 1998; 1999a) and East Asia (Leung et al., 1999a) have been found to compare very well with observations. The subgrid method significantly improves the simulation of surface temperature, precipitation, and snowpack over mountainous areas.

The distributed hydrology used in the modeling system is the Distributed-Hydrology-Soil-Vegetation Model (DHSVM) (Wigmosta et al., 1994). The model provides an integrated representation of watershed processes at the spatial scale described by Digital Elevation Model (DEM) data. The modeled landscape is divided into computational grid cells centered on DEM elevation nodes. Digital elevation data are used to model topographic controls on absorbed shortwave radiation, precipitation, air temperature, and down-slope water movement. Evapo-transpiration from vegetation is modeled using a Penman-Monteith approach. Solar radiation and wind speed are attenuated through the vegetation canopy based on cover density and Leaf Area Index (LAI). Snow accumulation and melt are simulated using a two-layer energy-balance model that explicitly incorporates the effects of topography and vegetation cover on the energy exchange at the snow surface. Individual grid cells are hydrologically linked through surface and subsurface flow routing. Each grid cell exchanges water with its adjacent neighbors as a function

of local hydraulic conditions resulting in a transient, three-dimensional representation of surface and saturated subsurface flow. As water moves downslope it may be intercepted by a stream channel. This intercepted water is routed through the channel network to the basin outlet. Model output includes streamflow at any point in the channel network and the spatial distribution of snow cover, snow water equivalent, and soil moisture.
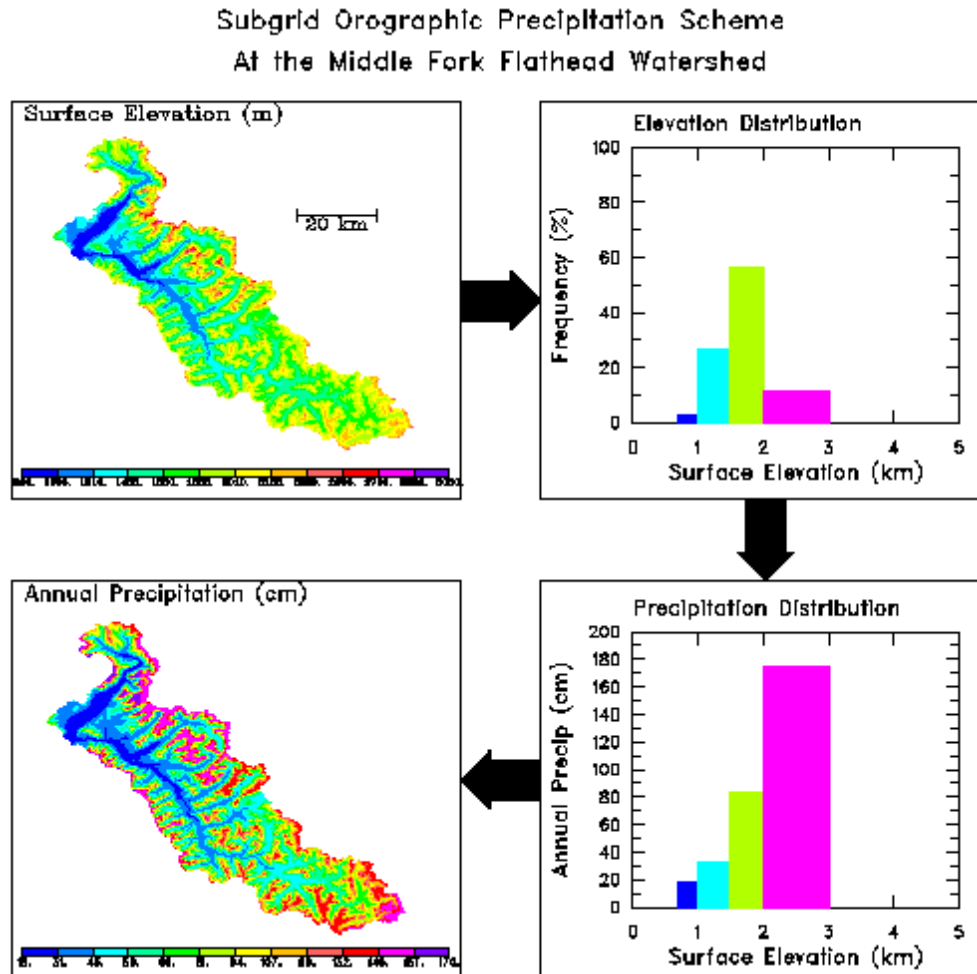

Figure 1. A schematic illustration of the subgrid parameterization of orographic precipitation applied to the Middle Fork Flathead watershed. Upper left: surface topography of the watershed at 1 km spatial resolution. Upper right: subgrid elevation classification. Lower right: simulations of precipitation at each subgrid elevation class. Lower left: mapping of precipitation to the watershed geographical area based on elevation to yield high spatial resolution distribution of climate conditions for driving hydrology models.

For most applications, DHSVM was driven by observed surface temperature, precipitation, surface pressure, surface humidity and wind, or that simulated by the RCM. The RCM can be driven by observed atmospheric circulation or simulations from General Circulation Models (GCM).

Applications

a. Impacts of climate change on mountain water resources

Global climate change due to increasing concentrations of greenhouse gases has stimulated numerous studies and discussions about its possible impacts on water resources. Climate scenarios generated by climate models at spatial resolutions ranging from about 50 km to 400 km do not provide enough spatial specificity for use in impact assessment over the western U.S. Leung and Ghan (1999a&b) described a climate sensitivity experiment where global climate simulations of the present (control) and $2xCO_2$ conditions were downscaled using the PNNL regional climate model. By comparing the GCM and RCM simulated climatology with observations, Leung and Ghan showed that the regional model greatly improves the simulations of precipitation, surface temperature, and snow cover at the local scales over the Pacific Northwest. The RCM is found to correctly capture the surface temperature/precipitation variations as functions of surface topography over different mountain ranges, and under different climate regimes.

The climate sensitivity experiment suggested that there is a warming of about 2^oC and precipitation generally increases over the Pacific Northwest and decreases over California. The combined effects of surface temperature and precipitation changes are such that snow cover is reduced by up to 50% on average, causing large changes in the seasonal runoff. Without the use of downscaling, GCMs were unable to capture the seasonal snowpack over the mountainous west coast. This limits the applicability of GCMs for addressing water resources issues under climate change conditions.

Leung and Wigmosta (1999) described the use of DHSVM to study the impacts of climate change on two mountain watersheds in the Pacific Northwest. The American River watershed covers an area of 204 km^2, with elevation that ranges between 849 m and 2102 m. Runoff is snowmelt dominated, with multiple peaks occurring between November and June. The Middle Fork Flathead covers an area of 2900 km^2, with elevation ranges between 959 m and 3047 m. Runoff is also snowmelt dominated, with a single peak that normally occurs between May and June.
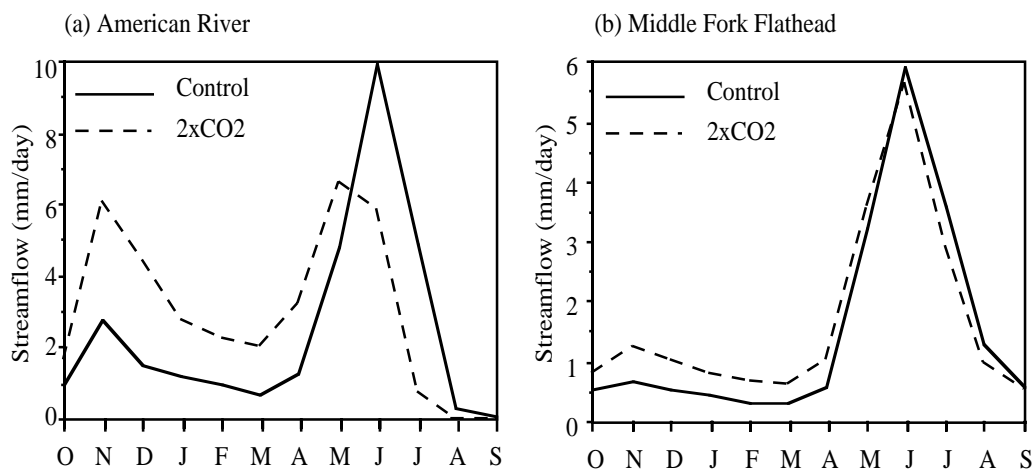

Figure 2: DHSVM simulated streamflow at (a) the American River and (b) Middle Fork Flathead for the control and $2xCO_2$ conditions

Figure 2 shows the streamflow simulated by DHSVM as it was driven by the control and $2xCO_2$ RCM simulations. The change in the hydrologic conditions is rather drastic over the American River. Because of the warmer temperature, snowpack is reduced by about 60% and

timing of streamflow is changed. There is a higher likelihood of wintertime flooding and reduced water supply during the summer. Over the Middle Fork Flathead, snowpack is only reduced by 12% and the seasonal pattern of streamflow remains intact.

Similar numerical experiments will be performed to understand the sensitivity of water resources to climate change in northern China. Collaborations have been established between PNNL and the National Climate Center (NCC), China Meteorological Administration (CMA) as part of a bilateral agreement between the U.S. Department of Energy and CMA on Regional Climate Study. Leung et al. (1999) evaluated the performance of three RCMs for simulating the 1991 summer monsoon conditions over China. Currently DHSVM has also been calibrated to simulate hydrological conditions over the Luan River basin and Hai River basin in northern China.

b. Simulations of the ENSO hydroclimate signals over the Columbia River basin

Natural fluctuations in the atmosphere-ocean system related to the El-Nino Southern Oscillation (ENSO) induce climate variability over many parts of the world. While evidence for predictability in the tropics has long been demonstrated, quantitative assessment of the prediction skill that can be achieved over the extratropics has only been recently reported. These studies suggest that although atmospheric variability in the extratropics is often dominated by chaotic dynamics associated with atmospheric flows, there is certain skill in predicting seasonal variability. This skill depends on the season and strength of the ENSO events, and varies geographically.

Recently, Livezey et al. (1996) analyzed the prediction skill of climate forecasts in the Pacific/North America region made by dynamical models using a two tiered approach. Their study indicates that the prediction skill associated with these dynamical forecasts is comparable, if not higher than, the corresponding official forecasts produced mainly by statistical models. Despite the efforts of ongoing research to improve AGCMs for refining the skill of climate predictions, limitations in the physical representations and the coarse spatial resolution used by AGCMs still present a serious problem when the models are put to practical use. One central issue relates to the specificity of the dynamical seasonal climate forecasts, that is, are they provided with enough accuracy and spatial resolution to be of value in managing natural resources? For example, can climate forecasts be applied directly to drive operational hydrology models for water resources planning?

We have examined the potential of using a model nesting approach to provide seasonal climate and streamflow forecasts suitable for water resources management. Two ensembles of perpetual January simulations were performed with a regional climate model driven by a GCM, using observed climatological sea surface temperature (SST) and the mean SST of the warm ENSO years between 1950-1994. The climate simulations were then used to drive a macroscale hydrology model to simulate streamflow. The differences between the two ensembles of simulations are defined as the warm ENSO signals.

The simulated hydroclimate signals were compared with observations. The analyses focus on the Columbia River basin in the Pacific Northwest. The Columbia River basin drains parts of British Columbia and seven different states in the U.S. Pacific Northwest, covering a total area of 567,000 sq.km. Winter snow accumulation and spring snowmelt dominate runoff production within the basin. The river system is highly managed for electric power generation, flood control, irrigation, flow enhancement, fishery and wildlife protection, navigation, and recreation. There are more than 250 reservoirs and 100 hydroelectric projects in the river system. Observational data analyses have already shown that there are statistically significant and coherent hydroclimate

signals over the Pacific Northwest associated with the ENSO. Under warm SST conditions in the tropical Pacific, the Pacific Northwest winter is warmer and dryer than the climatological mean condition, and the trend is generally reversed for the cold SST conditions. As a result, the mean annual streamflow and the timing of streamflow in the Columbia River basin is affected by the ENSO events. The use of seasonal climate forecasts can potentially benefit the management of water resources in the river system, which is already under increasing stress due to the growing demand for water and changing water use priorities in the region.

Our simulation results show that the global and regional models simulated a warming over the Pacific Northwest that is quite close to the observations. The models also correctly captured the strong wet signal over California and the weak dry signal over the Pacific Northwest during warm ENSO years. The regional climate model consistently performed better than the GCM in simulating the spatial distribution of regional climate and climate signals. When the climate simulations were used to drive a macroscale hydrology model at the Columbia River basin, the simulated streamflow signal resembles that derived from hydrological simulations driven by observed climate. The streamflow simulations were considerably improved when a simple bias correction scheme was applied to the climate simulations. The coupled regional climate and macroscale hydrologic simulations demonstrate the prospect for generating and utilizing seasonal climate forecasts for managing reservoirs. More detail from this study can be found in Leung et al. (1999b).

Work is being funded by the GEWEX Continental Internatioanl Program (GCIP) to apply similar methods to examine the use of seasonal climate forecasts for managing water resources over the Appalachians (Tennessee river) in the Eastern Mississippi River basin. In particular, a multiobjective optimization algorithm will be applied to the hydrological forecasts to develop a single set of reservoir operating rules that balance the multiple, conflicting management objectives such as hydropower, irrigation, and flood control. The values of utilizing seasonal forecasts are indicated by a shift in the multiobjective tradeoff curve. Strategies will be explored to integrate an operational hydrological forecasting system with the dynamical approach proposed in this project to improve hydrological forecasts on both the shorter (hourly and daily) and longer (weekly to monthly) time scales. Similar methods can also be applied to study water resources management in the Huaihe and Yangtze river basins in China where summer monsoon precipitation is highly affected by ENSO.

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